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Sandia National Laboratories

The *Peridigm* Framework for Peridynamic Simulations

12th U.S. National Congress on Computational Mechanics

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NNSA National Nuclear Security Administration

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Outline

- Brief introduction to peridynamics
- The *Peridigm* code
  - Software design
  - Current capabilities
  - Extending *Peridigm*
- Performing an analysis with *Peridigm*
  - Discretization
  - Input deck
  - Post-processing
- Example analyses and ongoing work
  - Many!

Peridynamic Theory of Solid Mechanics

WHAT IS PERIDYNAMICS?

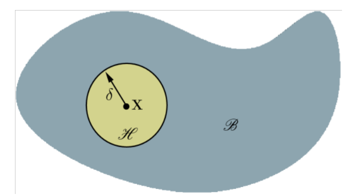
Peridynamics is a mathematical theory that unifies the mechanics of continuous media, cracks, and discrete particles.

HOW DOES IT WORK?

- Peridynamics is a *nonlocal* extension of continuum mechanics
- Remains valid in presence of discontinuities, including cracks
- Balance of linear momentum is based on an *integral equation*:

$$\rho(\mathbf{x})\ddot{\mathbf{u}}(\mathbf{x},t) = \underbrace{\int_{\mathscr{B}} \left\{ \underline{\mathbf{T}}[\mathbf{x},t]\left\langle \mathbf{x}' - \mathbf{x} \right\rangle - \underline{\mathbf{T}}'[\mathbf{x}',t]\left\langle \mathbf{x} - \mathbf{x}' \right\rangle \right\} \, \mathrm{d}V_{\mathbf{x}'}}_{\substack{\text{Divergence of stress replaced with} \\ \text{integral of nonlocal forces.}}} + \mathbf{b}(\mathbf{x},t)$$

The point X interacts directly with all points within its horizon



S.A. Silling. Reformulation of elasticity theory for discontinuities and long-range forces. *Journal of the Mechanics and Physics of Solids*, 48:175-209, 2000.

Silling, S.A. and Lehoucq, R. B. Peridynamic Theory of Solid Mechanics. *Advances in Applied Mechanics* 44:73-168, 2010.

Peridynamic Theory of Solid Mechanics

CONSTITUTIVE LAWS IN PERIDYNAMICS

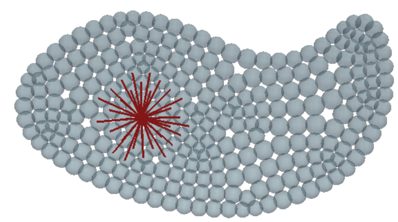
- Peridynamic *bonds* connect any two material points that interact directly
- Peridynamic forces are determined by force states acting on bonds

$$\underbrace{\underline{\mathbf{T}}[\mathbf{x},t]}_{\text{Force State}} \quad \underbrace{\langle \mathbf{x}_i' - \mathbf{x}\rangle}_{\text{Bond}}$$

- Force states are constitutive laws that are functions of the deformations of all points within a neighborhood
- *Material failure* is modeled through the breaking of peridynamic bonds

DISCRETIZATION OF A PERIDYNAMIC BODY

- A body may be represented by a finite number of particles (sphere elements) [1]



$$\rho(\mathbf{x})\ddot{\mathbf{u}}_h(\mathbf{x},t) = \sum_{i=0}^{N} \left\{ \underline{\mathbf{T}}[\mathbf{x},t]\left\langle \mathbf{x}_i' - \mathbf{x}\right\rangle - \underline{\mathbf{T}}'[\mathbf{x}_i',t]\left\langle \mathbf{x} - \mathbf{x}_i'\right\rangle \right\} \Delta V_{\mathbf{x}_i'} + \mathbf{b}(\mathbf{x},t)$$

1. Silling, S.A. and Askari, E. A meshfree method based on the peridynamic model of solid mechanics. *Computers and Structures* 83:1526-1535, 2005.

Constitutive Models for Peridynamics

PERIDYNAMIC FORCE STATES MAP BONDS TO PAIRWISE FORCE DENSITIES

- Peridynamic constitutive laws can be grouped into two categories
  - *Bond-based*: bond forces depend only on a single pair of material points
  - *State-based*: bond forces depend on deformations of all neighboring material points

Microelastic Material [1]

- Bond-based constitutive model
- Pairwise forces are a function of bond stretch

$$s = \frac{y - x}{x}$$

- Magnitude of pairwise force density given by

$$\underline{t} = \frac{18k}{\pi\delta^4} s$$

Linear Peridynamic Solid [2]

- State-based constitutive model
- Deformation decomposed into deviatoric and dilatational components

$$\theta = \frac{3}{m} \int_{\mathcal{H}} (\underline{\omega}\, \underline{x}) \cdot \underline{e}\, dV \qquad \underline{e}^d = \underline{e} - \frac{\theta\, \underline{x}}{3}$$

- Magnitude of pairwise force density given by

$$\underline{t} = \frac{3k\theta}{m}\, \underline{\omega}\, \underline{\mathrm{x}} + \frac{15\mu}{m}\, \underline{\omega}\, \underline{e}^{\mathrm{d}}$$

Definitions

$\underline{x}$	bond vector
x	initial bond length
y	deformed bond length
s	bond stretch
$\underline{e}$	bond extension
$\underline{e}^d$	deviatoric bond extension
$\underline{\omega}$	influence function
V	volume
$\mathcal{H}$	neighborhod
m	weighted volume
θ	dilatation
δ	horizon
k	bulk modulus
μ	shear modulus
$\underline{t}$	pairwise force density

1. S.A. Silling. Reformulation of elasticity theory for discontinuities and long-range forces. *Journal of the Mechanics and Physics of Solids*, 48:175-209, 2000.
2. S.A. Silling, M. Epton, O. Weckner, J. Xu, and E. Askari, Peridynamic states and constitutive modeling, *Journal of Elasticity*, 88, 2007.

Classical Material Models Can Be Applied in Peridynamics

CORRESPONDENCE APPROACH RESULTS IN A NON-ORDINARY STATE-BASED MATERIAL MODEL [1]

- Approximate deformation gradient based on initial and current locations of material points in family

Approximate Deformation Gradient

$$\bar{\mathbf{F}} = \left(\underline{\mathbf{Y}} * \underline{\mathbf{X}}\right)\mathbf{K}^{-1}$$

Shape Tensor

$$\mathbf{K} = \underline{\mathbf{X}} * \underline{\mathbf{X}}$$

Definitions

$\underline{\mathbf{X}}$	reference position vector state
$\underline{\mathbf{Y}}$	deformation vector state
$\mathbf{K}$	shape tensor
$\bar{\mathbf{F}}$	approximate deformation gradient
ξ	bond
$\underline{\omega}$	influence function
σ	Piola stress

- Kinematic data passed to classical material model
- Classical material model computes stress
- Stress converted to pairwise force density

$$\underline{\mathbf{T}}\left\langle\xi\right\rangle = \underline{\omega}\left\langle\xi\right\rangle\,\sigma\mathbf{K}^{-1}\xi$$

- Suppression of zero-energy modes (optional) [2]

1. S.A. Silling, M. Epton, O. Weckner, J. Xu, and E. Askari, Peridynamic states and constitutive modeling, *Journal of Elasticity*, 88, 2007.
2. Littlewood, D. A Nonlocal Approach to Modeling Crack Nucleation in AA 7075-T651. Proceedings of the ASME 2011 International Mechanical Engineering Congress and Exposition, Denver, Colorado, 2011.

Relationship between Classical and Peridynamic Theories

PERIDYNAMIC OPERATORS ARE ANALOGUES OF THE CLASSICAL THEORY

Relation	Peridynamic Theory	Standard Theory
Kinematics	$\underline{\mathbf{Y}}\langle \mathbf{x}' - \mathbf{x}\rangle = \mathbf{y}(\mathbf{x}') - \mathbf{y}(\mathbf{x})$	$\mathbf{F} = \frac{\partial \mathbf{y}}{\partial \mathbf{x}}(\mathbf{x})$
Linear Momentum Balance	$\rho\ddot{\mathrm{u}}(\mathrm{x}) = \int_{\mathcal{H}_\mathrm{x}} \{\underline{\mathrm{T}}[\mathrm{x}, t]\langle \mathrm{x}' - \mathrm{x}\rangle - \underline{\mathrm{T}}[\mathrm{x}', t]\langle \mathrm{x} - \mathrm{x}'\rangle\}\, dV_{\mathrm{x}'} + \mathrm{b}(\mathrm{x})$	$\rho\ddot{\mathrm{u}}(\mathrm{x}) = \nabla \cdot \boldsymbol{\sigma}(\mathrm{x}) + \mathrm{b}(\mathrm{x})$
Constitutive Model	$\underline{\mathbf{T}} = \widehat{\underline{\mathbf{T}}}(\underline{\mathbf{Y}})$	$\boldsymbol{\sigma} = \widehat{\boldsymbol{\sigma}}(\mathbf{F})$
Angular Momentum Balance	$\int_{\mathcal{H}_\mathrm{x}} \{\underline{\mathbf{Y}}\langle \mathbf{x}' - \mathbf{x}\rangle \times \underline{\mathbf{T}}\langle \mathbf{x}' - \mathbf{x}\rangle\}\, dV_{\mathbf{x}'} = 0$	$\boldsymbol{\sigma} = \boldsymbol{\sigma}^T$

Material Failure Is Controlled by a Bond-Failure Law

THE CRITICAL-STRETCH MODEL IS THE SIMPLEST BOND-FAILURE LAW [1]

- A bonds fails when its extension exceeds a critical value
- Bond failure is irreversible

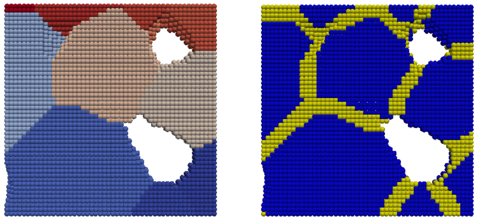
$$s_{\max} = \frac{\|\underline{e}\|_{\max}}{\|\underline{x}\|}$$

$$\phi = \begin{cases} 0 & \text{if} \quad s_{\max} < s_{\text{crit}} \\ 1 & \text{if} \quad s_{\max} \geq s_{\text{crit}} \end{cases}$$

- Damage results from the accumulation of broken bonds
- Critical stretch parameter is tied to the energy release rate (experimentally measureable)

Example: Modified critical-stretch law for polycrystalline materials [2]

- Modified critical-stretch law for failure of polycrystalline material



- Bond failure law favors material damage along grain boundaries
- Contact algorithm controls material interactions after bonds are broken

1. Silling, S.A. and Askari, E. A meshfree method based on the peridynamic model of solid mechanics. *Computers and Structures* 83:1526-1535, 2005.

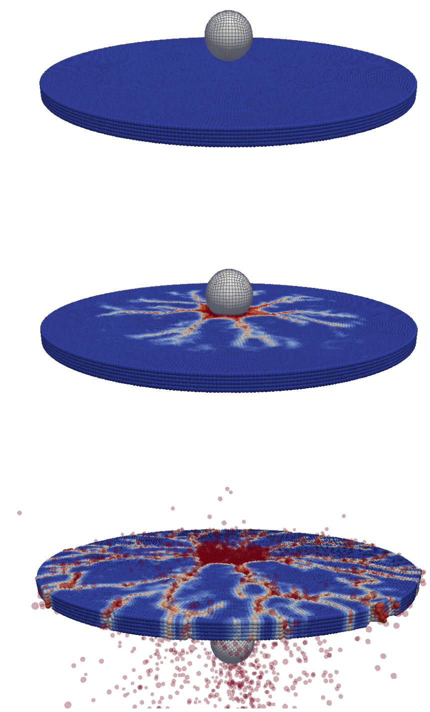
2. D. Littlewood, V. Tikare, and J. Bignell. Informing Macroscale Constitutive Laws through Modeling of Grain-Scale Mechanisms in Plutonium Oxide. Workshop on Nonlocal Damage and Failure: Peridynamics and Other Nonlocal Models, San Antonio, Texas, March 11-12 2013.

Contact in Peridynamic Simulations

- Contact algorithms involve two distinct steps
  - Proximity search
  - Enforcement of the contact model
- A *short-range force* approach has been used in the majority of peridynamic simulations to date [1]
  - Spring-like repulsive force
  - Active when relative distance, *r*, is below contact radius, r_c

$$f_{\mathrm{c}} = \begin{cases} C\left(r_{\mathrm{c}} - r\right)\Delta V_1 \Delta V_2 & \text{if} \quad r \leq r_{\mathrm{c}} \\ 0 & \text{if} \quad r > r_{\mathrm{c}} \end{cases}$$

  - Does not require explicit definition of contact surfaces
  - Friction may be incorporated by decomposing relative motion into normal and tangential components
- More sophisticated contact models are possible
  - Example: iterative penalty enforcement to drive the contact gap to zero [2]



Simulation of brittle fracture

1. Silling, S.A. and Askari, E. A meshfree method based on the peridynamic model of solid mechanics. *Computers and Structures* 83:1526-1535, 2005.
2. SIERRA Solid Mechanics Team, Sierra/SolidMechanics 4.22 user's guide, SAND Report 2011-7597, Sandia National Laboratories, Albuquerque, NM and Livermore, CA, 2011.

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- Brief introduction to peridynamics
- The *Peridigm* code
  - Software design
  - Current capabilities
  - Extending *Peridigm*
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  - Discretization
  - Input deck
  - Post-processing
- Example analyses and ongoing work

The *Peridigm* Computational Peridynamics Code

Sandia National Laboratories

WHAT IS PERIDIGM?

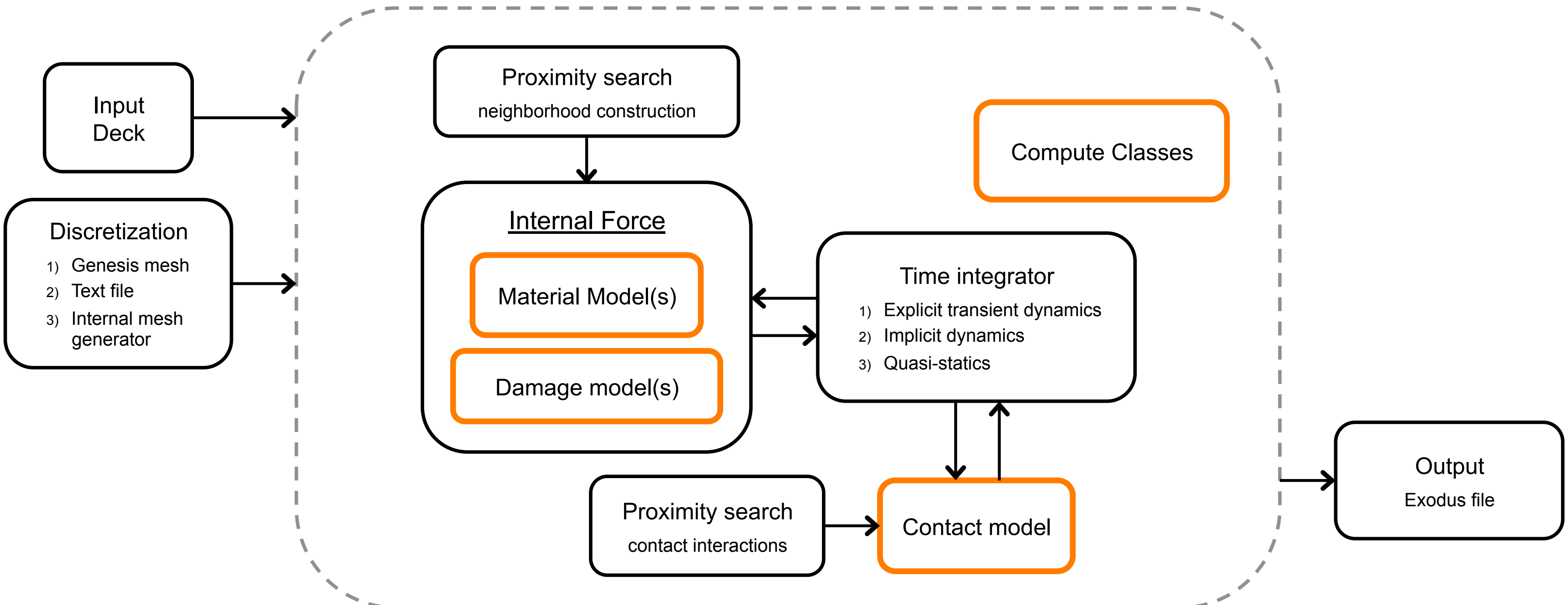
- Open-source software developed at Sandia National Laboratories
- C++ code based on Sandia's *Trilinos* project
- Platform for multi-physics peridynamic simulations
- Capabilities:
  - State-based constitutive models
  - Implicit and explicit time integration
  - Contact for transient dynamics
  - Large-scale parallel simulations
- Compatible with pre- and post-processing tools
  - Cubit mesh generation
  - Paraview visualization tools
  - SEACAS utilities
- Designed for extensibility

M.L. Parks, D.J. Littlewood, J.A. Mitchell, and S.A. Silling, Peridigm Users' Guide v1.0.0. Sandia Report SAND2012-7800, 2012.

Peridigm Code Architecture

DESIGN GOALS:

- State-based peridynamics
- Explicit and Implicit time integration
- Contact
- Massively parallel
- Performance
- Extensibility



Orange denotes extensible components

Time Integration

AVAILABLE INTEGRATION SCHEMES

- Explicit dynamics: Velocity-Verlet (leapfrog) time integrator
- Implicit dynamics: Newmark-beta
- Quasi-statics: Nonlinear solver with modified Newton approach

LINEAR SOLVERS

- Iterative Krylov methods, parallel scalability
- Conjugate gradient solver (default solver)
- Wide variety of options available through the *Trilinos NOX* package

CONSTRUCTION OF THE TANGENT MATRIX

- Three options for construction of the tangent matrix:
  - User-supplied tangent
  - Finite-difference scheme
  - *Automatic differentiation* via the *Trilinos Sacado* package
- Finite-difference scheme operates directly on internal-force calculation
  - No additional development required by material model developer
- Automatic differentiation approach requires C++ templates and (minor) extension of material model

Available in Peridigm as of July 2013

MATERIAL MODELS

- Linear peridynamic solid [1]
- Elastic-perfectly-plastic [2]
- Elastic-plastic with isotropic hardening [3]
- Viscoelastic [4]
- Thermoelastic (thermal strains)

DAMAGE MODELS

- Critical stretch [5]

CONTACT MODELS

- Short-range force model [5]
- Short-range force model with friction

COMPUTE CLASSES

- Output of any node or element variable
- Per-block quantities (min, max, sum)
- Energy (kinetic, stored elastic)
- Neighborhood statistics (horizon, number of neighbors)
- Approximate deformation gradient [1]
- Many others…

1. S.A. Silling, M. Epton, O. Weckner, J. Xu, and E. Askari, Peridynamic states and constitutive modeling, *Journal of Elasticity*, 88, 2007.
2. J.A. Mitchell. A nonlocal, ordinary, state-based plasticity model for peridynamics. Sandia Report SAND2011-3166, 2011.
3. J.T. Foster, D.J. Littlewood, J.A. Mitchell, and M.L. Parks. Implicit-time integration of an ordinary state-based peridynamic plasticity model with isotropic hardening. ASME International Mechanical Engineering Congress and Exposition, Houston, Texas, November 9-15, 2012.
4. J.A. Mitchell. A non-local, ordinary-state-based viscoelasticity model for peridynamics, Sandia Report SAND2011-8064, 2011.
5. Silling, S.A. and Askari, E. A meshfree method based on the peridynamic model of solid mechanics. *Computers and Structures* 83:1526-1535, 2005.

Extending Peridigm: Adding a Material Model

- Peridigm material models derive from the `Material` base class
- Specify required data fields
- Required routines

```
void computeForce(const double dt,
                  const int numOwnedPoints,
                  const int* ownedIDs,
                  const int* neighborhoodList,
                  DataManager& dataManager) const;
```

- Optional routines

```
void initialize(const double dt,
                const int numOwnedPoints,
                const int* ownedIDs,
                const int* neighborhoodList,
                DataManager& dataManager) const;

void computeJacobian(const double dt,
                     const int numOwnedPoints,
                     const int* ownedIDs,
                     const int* neighborhoodList,
                     DataManager& dataManager,
                     SerialMatrix& jacobian,
                     JacobianType jacobianType)) const ;

Others…
```

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Performing an Analysis with Peridigm

CREATING A DISCRETIZATION

Option 1) Genesis file

- Cubit mesh generator (hexahedron or tetrahedron mesh)
- Designate blocks and node sets
- Genesis sphere meshes also supported

Option 2) Text file

- Discretization defined by (coordinates, volume, block id) at each node
- User-supplied node sets (lists of node ids)
- Supports EMU input files

Option 3) Internal mesh generator

- Rectangular or cylindrical solid
- Restricted to single block
- User-supplied node sets (lists of node ids)

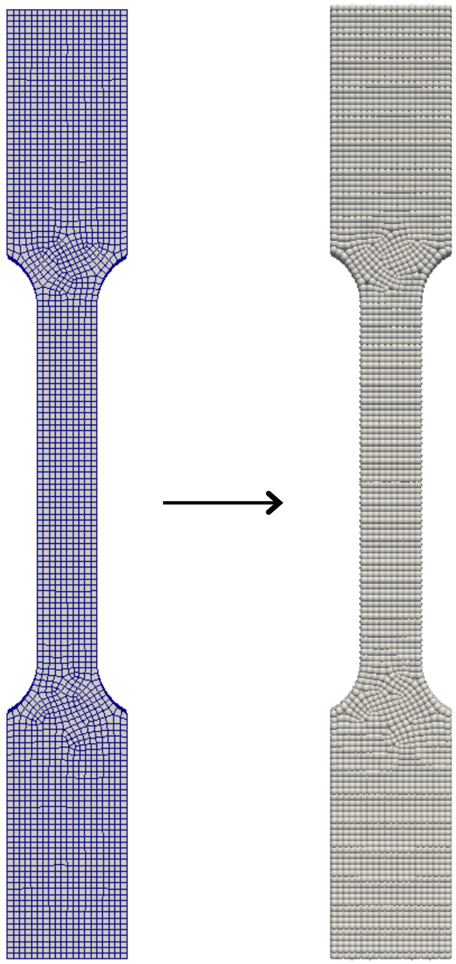


Illustration of *Peridigm* conversion from hexahedron mesh to sphere mesh

Performing an Analysis with Peridigm

CREATING AN INPUT DECK

```
Discretization
    Type "Exodus"
    Input Mesh File "tensile_test.g"

Materials
    My Material
      Material Model "Elastic"
      Density 8.0
      Bulk Modulus 1.500e12
      Shear Modulus 6.923e11

Blocks
    My Block
        Block Names "block_1 block_2 block_3"
        Material "My Material"
        Horizon {0.1900*2.1/2.0}

Boundary Conditions
    Prescribed Displacement Bottom
        Type "Prescribed Displacement"
        Node Set "nodelist_1"
        Coordinate "y"
        Value "y*0.01*t"
    …
```

[Current input-deck format courtesy Foster research group, UTSA]

Performing an Analysis with Peridigm

CREATING AN INPUT DECK (CONTINUED)

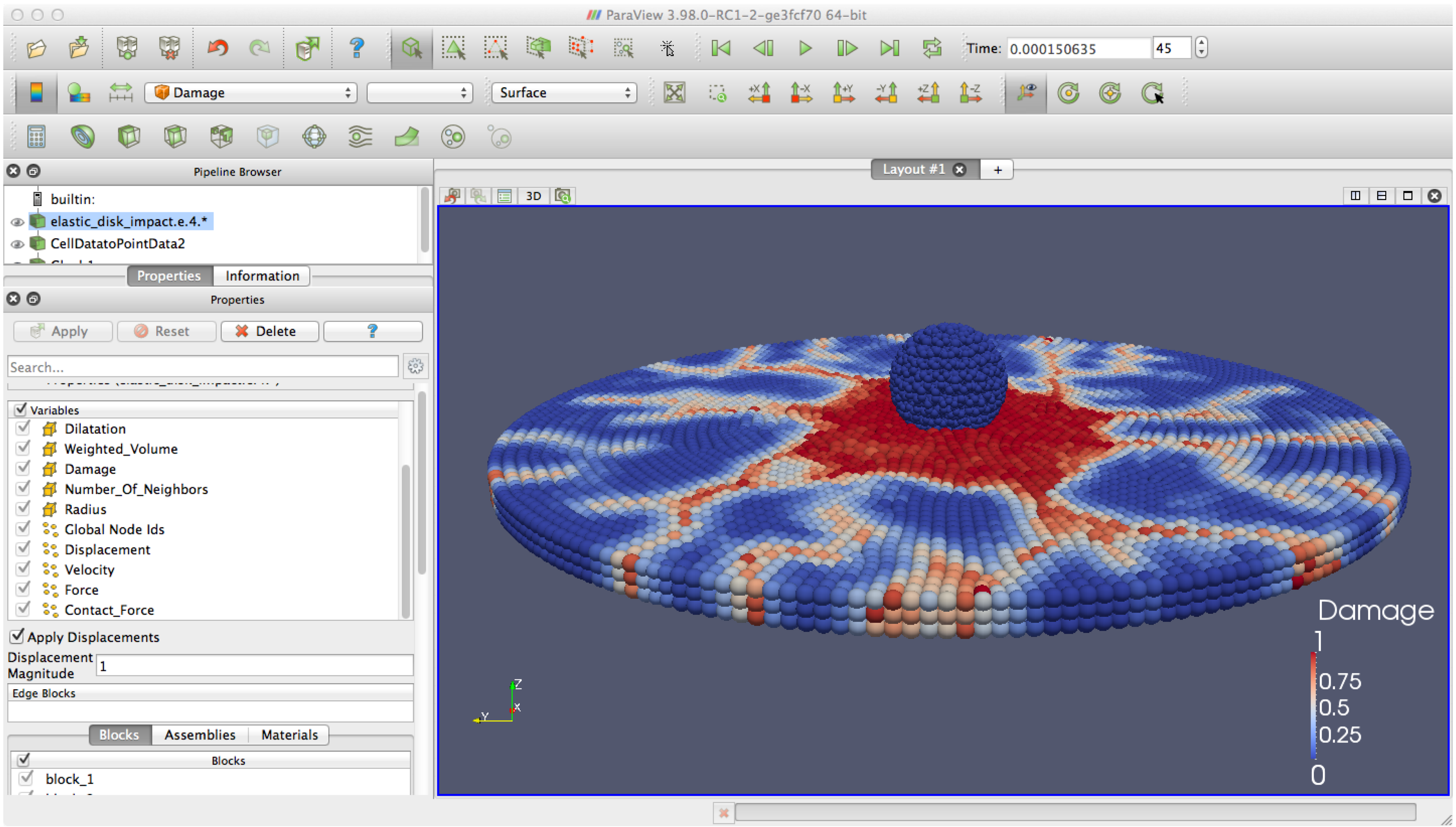
```
Solver
    Initial Time 0.0
    Final Time 1.0
    QuasiStatic
        Number of Load Steps 4
        Absolute Tolerance 1.0
        Maximum Solver Iterations 10

Compute Class Parameters
    Strain Gage Top Displacement
        Compute Class "Nearest_Point_Data"
        X 0.0
        Y 1.27
        Z 0.0
        Variable "Displacement"
        Output Label "Gage_Top_Displacement"

Output
    Output File Type "ExodusII"
    Output Filename "tensile_test"
    Output Frequency 1
    Output Variables
        Dilatation "true"
        Gage_Top_Displacement "true"
        …
```

Performing an Analysis with Peridigm

POST-PROCESSING WITH PARAVIEW [1]



1. www.paraview.org

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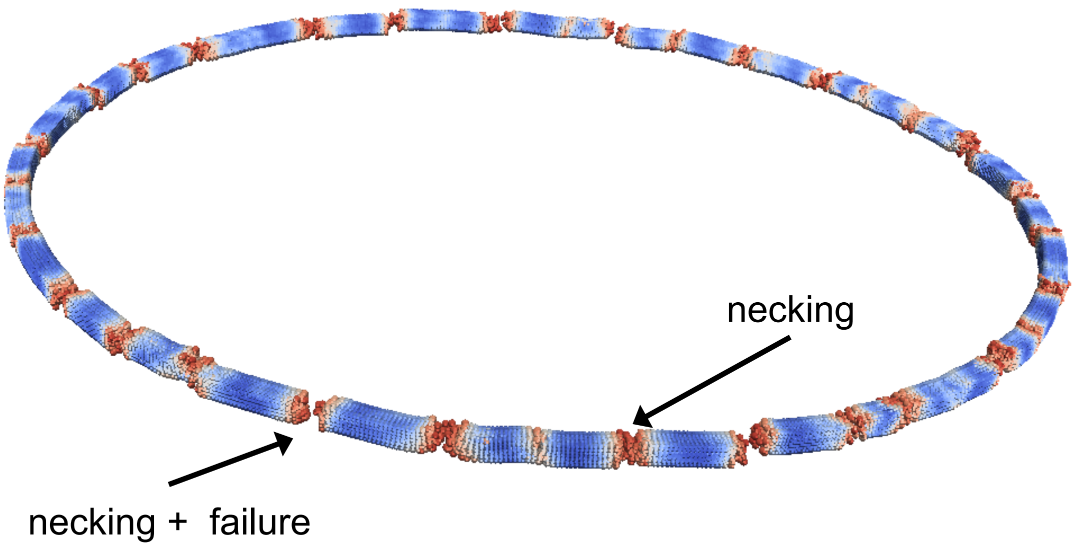
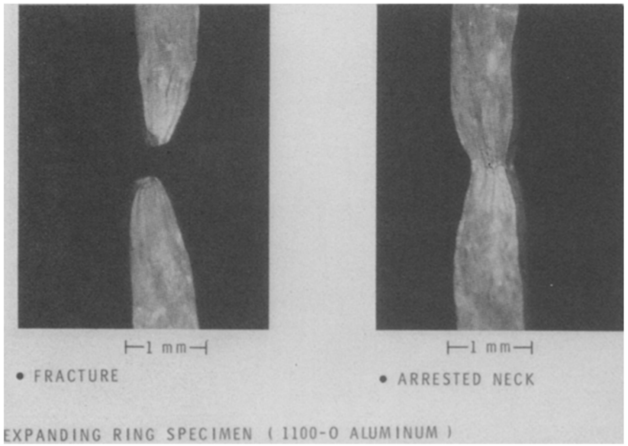
Elastic-Plastic Material Model

PERIDIGM PREDICTS NECKING AND FRAGMENTATION OF EXPANDING RING

- Motivated by ring fragmentation experiments of Grady and Benson [1]
  - 1100-0 aluminum ring (ductile)
- Modeled in Peridigm with elastic-perfectly-plastic constitutive model [2]





Fracture and arrested neck region from electromagnetically-loaded expanding ring [1]

1. D. Grady and D. Benson. Fragmentation of metal rings by electromagnetic loading, *Experimental Mechanics,* 23(4), 1983.
2. J.A. Mitchell. A nonlocal, ordinary, state-based plasticity model for peridynamics. Sandia Report SAND2011-3166, 2011.

Thermoelastic Material Model

MODIFY BOND EXTENSION TO INCORPORATE THERMAL EXPANSION / CONTRACTION

Thermoelastic Linear Peridynamic Solid

- Linear relationship between temperature change and thermal bond extension

$$\underline{e}^{\text{thermal}} = \alpha\,\Delta T\,\underline{x}$$

where α is the thermal expansion coefficient

- Subtract thermal extension from total extension

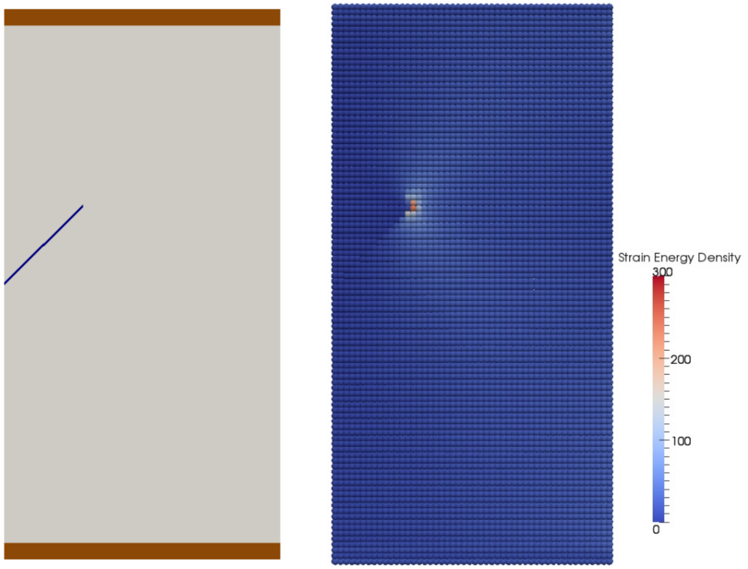
$$\underline{e}^{*} = \underline{e} - \underline{e}^{\text{thermal}} = \underline{e} - \alpha\,\Delta T\,\underline{x}$$

$$\theta^{*} = \int_{\mathcal{H}} \frac{3}{m}\,(\underline{\omega}\,\underline{x}) \cdot \underline{e}^{*}\,dV$$

$$\underline{e}^{*d} = \underline{e}^{*} - \frac{\theta^{*}\,\underline{x}}{3}$$

$$\underline{t}^{*} = \frac{3k\theta^{*}}{m}\underline{\omega}\,\underline{x} + \frac{15\mu}{m}\underline{\omega}\,\underline{e}^{*d}$$

Pre-cracked plate under thermal load



- Fixed displacement at ends of plate
- Uniform temperature reduction
- Strain energy concentration results at crack tip

Drucker-Prager Plasticity Model

PRESSURE-DEPENDENT YIELD CONDITION APPLICIABLE TO CONCRETE & SOIL

- Ongoing research on nonlocal analog of linear Druker-Prager plasticity model
  - Pressure-dependent peridynamic yield criterion and flow rule
  - Motivated by pressure-dependent material response over multiple length scales
  - Dissipation-governed bond failure law also under development

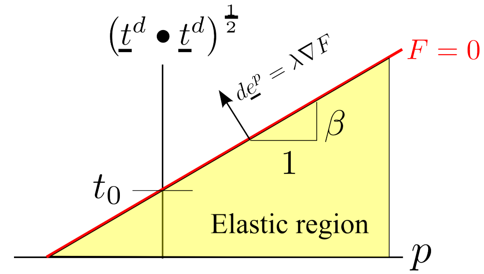
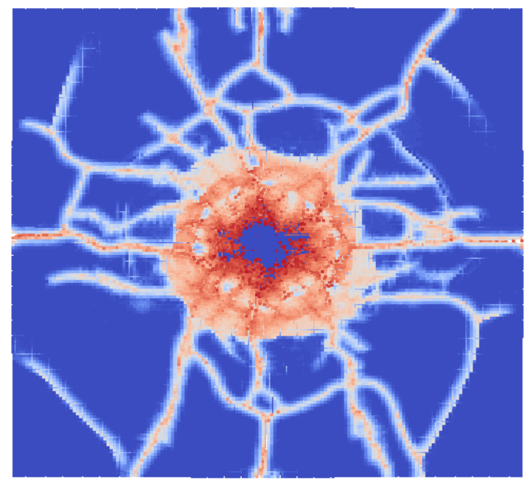


Illustration of plastic flow rule

Goal: Analyze multiscale, dynamic failure of concrete during impact



Simulated concrete impact

[Christopher Lammi]

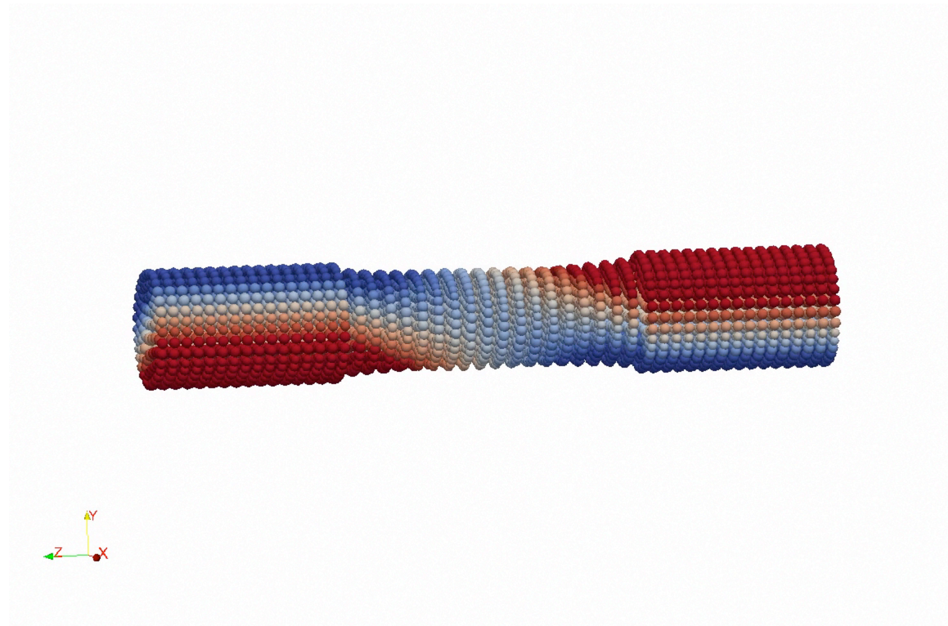
Quasi-static Preload for Transient Dynamics Simulation

SINGLE SIMULATION ENCORPORATING MULTIPLE TIME INTEGRATION SCHEMES

- Employ multiple solvers

```
Solver1
  Initial Time 0.0
  Final Time 0.6
  QuasiStatic
    Number of Load Steps 6
    Absolute Tolerance 1.0
    Maximum Solver Iterations 100

Solver2
  Initial Time 0.6
  Final Time 0.601
  Verlet
    Fixed dt 1.5e-7
```



- Utilize ternary operator in definition of boundary conditions

```
Boundary Conditions
  Prescribed Displacement Bottom x
    Type "Prescribed Displacement"
    Node Set "nodelist_1"
    Coordinate "x"
    Value "t <= 0.6 ? x*cos(1.5*t)-y*sin(1.5*t) : x*cos(1.5*0.6)-y*sin(1.5*0.6)"
```

[John Foster]

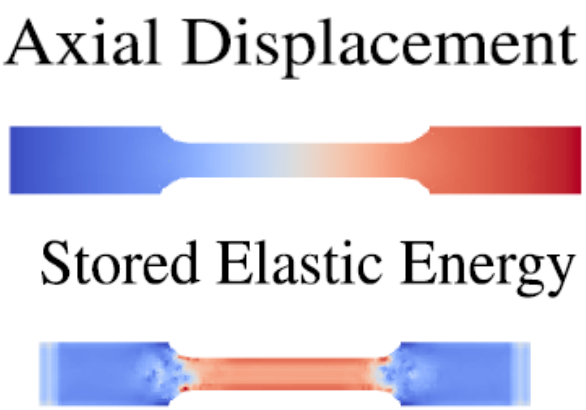
Surface Correction Factor

CHALLENGE

- The majority of peridynamic material models were derived based on bulk response
- Material points close to the surface have reduced nonlocal region (fewer bonds) than material points in the bulk
- Ordinary peridynamic material models exhibit inconsistencies at the surface

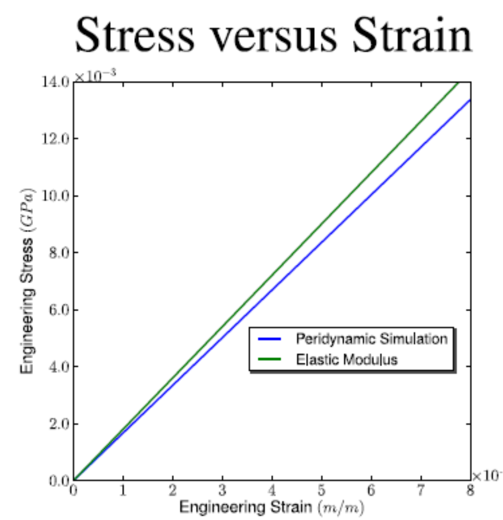
POTENTIAL SOLUTION

- Modify material model near surfaces to mitigate surface effect



<u>Sources of Error</u>

1) Geometric surface effects
2) Nonlocal model (dilatation on surface) and related model properties
3) Discretization error



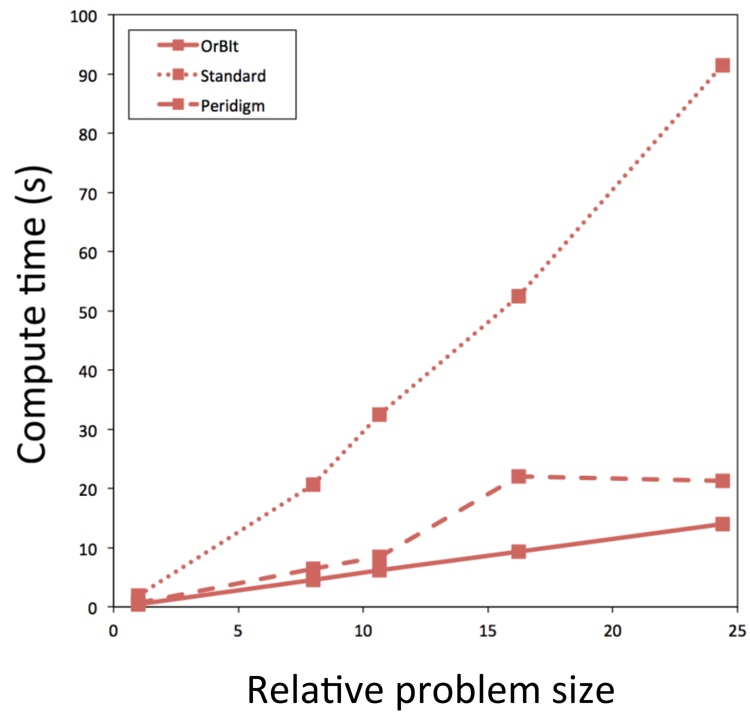
[John Mitchell]

Matrix Assembly via Bond Iteration

NOVEL MATRIX ASSEMBLY SCHEME REDUCES COST OF IMPLICIT ANALYSES

- Ongoing algorithmic research on assembly of nonlocal tangent stiffness matrix
- Initial results show 3-4 x speedup in assembly time over cell iteration
- Broken bonds can be removed from iteration loop
- Computes sensitivities for a single row simultaneously (saves on sparse matrix insertion)
- Simplified control of damage propagation in quasi-static analyses
- Applicable to current *Peridigm* code architecture

Comparison of serial assembly time

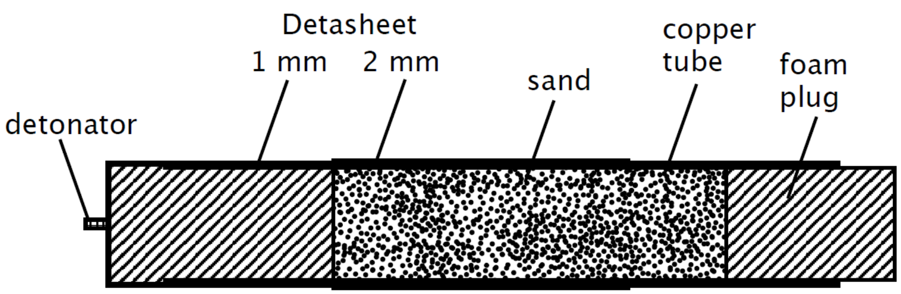


[Daniel Turner]

Explosively Compressed Cylinder

PERIDYNAMICS ENABLES MODELING OF PERVASIVE MATERIAL DAMAGE

- Motivated by experiments of Vogler and Lappo [1]
- Commonly used approach for consolidation of powders
- Copper cylinder filled with granular material and wrapped with Detasheet explosive
- Polyurethane foam plugs used to keep granular sample in tube



Cylinder schematic

Cylinder after compression

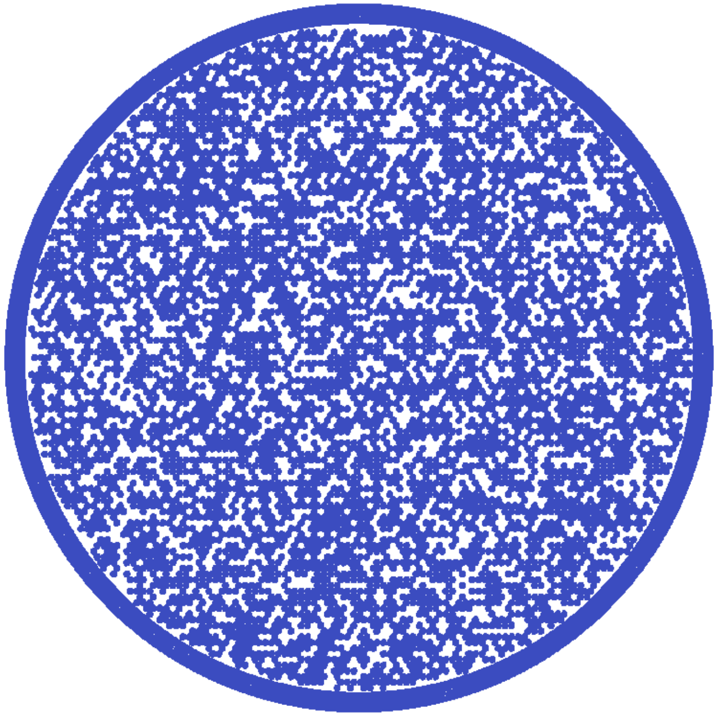
[Tracy Vogler]

1. T.J. Vogler and K.M. Lappo. Cylindrical compaction of granular ceramics: experiments and simulations, The 12th Hypervelocity Impact Symposium, 2012.

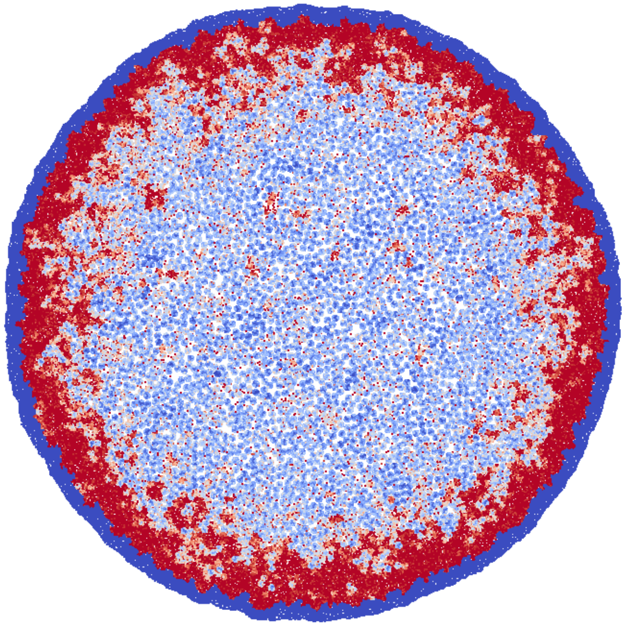
Explosively Compressed Cylinder

COMPUTATIONAL RESULTS OBTAINED WITH PERIDIGM

Before



After



Color denotes damage (percentage of broken bonds)

[Tracy Vogler, John Foster, Canio Hoffarth]

Improved Digital Image Correlation (DIC) using Peridynamic Damage Modeling

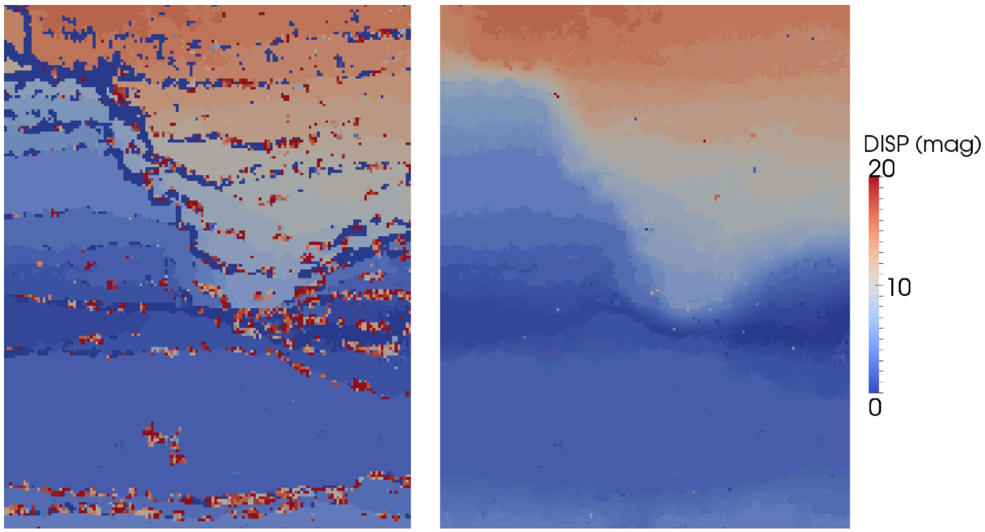
CHALLENGE

- DIC often fails near cracks or discontinuities
- Displacements obtained by interpolation across a crack are highly inaccurate

POTENTIAL SOLUTION

- Apply peridynamics to compute displacements in regions where DIC fails
- Treat the quality DIC displacements as boundary condition and solve for the remainder of the domain using a peridynamic model

Failure of fiber-reinforced concrete tensile specimen



Standard DIC
Dark blue regions denote failed correlation, spurious colors represent inaccurate displacements

Enhanced result
Peridynamic approach improves correlation

[Daniel Turner]

Application of Peridynamics to Digital Image

INITIAL RESULTS

- Computed damage profile closely matches experimental results
- Displacement (strain) accuracy is considerably improved

Failure of fiber-reinforced concrete tensile specimen

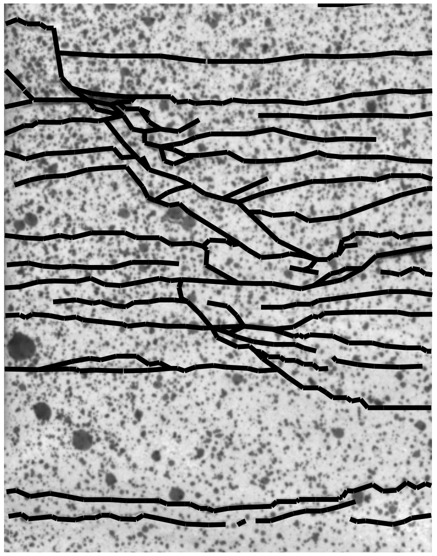
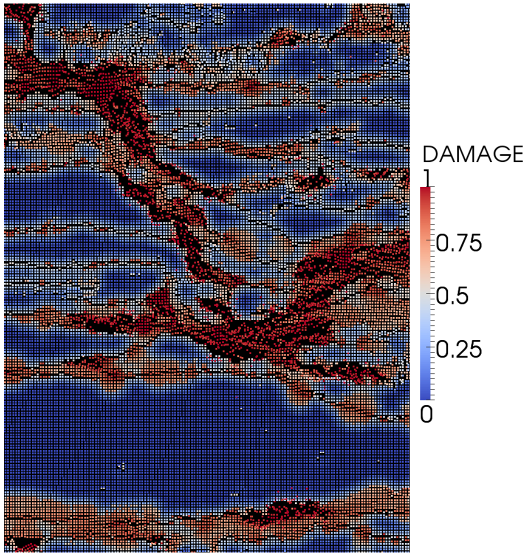


Photo of damaged concrete specimen

Lines indicate cracks



Peridynamic damage profile

[Daniel Turner]

Ongoing and Future Work

- Coupling to local models
  - Work underway to couple *Peridigm* with the classical FEM code *Albany*
- Expanded contact functionality
  - User-defined block-by-block contact interactions
  - Improved parallel proximity search
- Advanced control over bond initialization
  - Allow for bond cutting with mesh entities (*e.g.*, shell elements) [1]
- Bond failure in quasi-static simulations
  - Requires iterative solution of model problems

1. SIERRA Solid Mechanics Team, Sierra/SolidMechanics 4.22 user's guide, SAND Report 2011-7597, Sandia National Laboratories, Albuquerque, NM and Livermore, CA, 2011.

Questions?

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Peridigm Web Site

http://peridigm.sandia.gov